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COMPUTATIONAL EM MODELING CAPABILITIES AT LLNL FOR SURFACE, NEAR-SURFACE, AND UNDERGROUND ANTENNA FOR COMMUNICATION AND DETECTION ISSUES

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CONTENTS

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ABSTRACT

Electromagnetic propagation from sources just above or buried within the ground is an important consideration for remote detection applications, communications and antenna design, and geophysical exploration.

A useful tool to supplement experimental work, or as a first step in evaluating a system or phenomenon, is computer modeling. Within the last decade or so, codes have emerged which can be applied to complex real-world problems. Innovative computational electromagnetic modeling capabilities exist at Lawrence Livermore National Laboratory (LLNL) involving:

- point sources and approximate current distributions
- method-of-moments solution of integral equations
- time domain finite difference technique

These capabilities are being further developed at LLNL.

1. INTRODUCTION

The electromagnetic behavior of objects just above or buried within the ground is markedly different from the behavior of the same objects in free space. Objects of interest include antennas, shelters and geological anomalies, to name just a few. While analytic techniques have been developed to treat a few simple geometries [1], it has not been possible to treat the majority of complex real world systems analytically. Experiments with real-world systems are expensive, often prohibitively so, and it may not be possible to examine all the relevant parameters over their full ranges. An alternative to these two approaches is computational EM modeling.

Computational EM modeling was not that well developed a decade ago and was certainly not adequately developed and tested in the area of scattering and coupling in the presence of or within a lossy dielectric medium, i.e., earth. In the last decade or so, this picture has substantially changed. Along several developmental lines, codes have emerged, been tested, then refined, and finally validated that can treat real-world problems. The validation consists of comparing analytical or experimental results for simple objects with the corresponding computational results. The need for validation of computational modeling helps maintain an interest in analysis and experimentation, at least for simple geometries.

LLNL has three active areas of computational EM modeling applicable to underground systems that are supported analytically and experimentally. These three areas are based on different computational techniques, namely:

- Point Sources and Approximate Current Distributions
- Method-of-Moments Solution of Integral Equations
- Time Domain Finite Difference Technique

The first two can be classified as Green's Function techniques, being based on the field of a point source. The third involves the direct integration of the partial differential equations for the field. Each technique has its own advantages and adherents. Used in a complementary fashion and supported by analytical and experimental checks, they form a very powerful set of tools for answering a myriad of problems related to underground antennas, communications, and detection. This paper will describe these techniques in more detail and will provide an overview of their capabilities.

2. POINT SOURCES AND APPROXIMATE CURRENT DISTRIBUTIONS

The problem of numerically modeling an underground antenna can be separated into the steps of evaluating the field of a point source in the earth, determining the current on an actual antenna, and computing the field of this finite current distribution. The field of a point source in the earth can be obtained by numerical evaluation of infinite integrals over wave number (Sommerfeld integrals). Codes to evaluate these integrals by numerical integration along contours in the complex plane were developed by Lytle and Lager [2]. This was initially done for a homogeneous, lossy half-space with air above the interface (Fig. 1) and later extended to a medium of horizontal layers with differing conductivities and dielectric constants [3].

These codes can evaluate the fields of a point source in a stratified earth to high accuracy. The advantage of considering a point source is that the fields can be evaluated in considerably less time than the field of a finite antenna. Although input power cannot be evaluated, the point-source models can demonstrate the relative difficulty of communicating for specific frequencies, source types, and field orientations. The codes will model either electric or magnetic point dipoles which represent electrically small dipole or loop antennas, respectively.

2.1. CURRENT ON A FINITE ANTENNA

To determine the communication efficiency of a buried antenna, it is necessary to consider the size and shape of the antenna. On an antenna of finite size, the distribution of current must be determined for a given source voltage. This can be a difficult problem for an isolated antenna and is made more so when the antenna interacts with an interface and may have an insulating sheath. Antennas used in the earth are usually insulated to improve their efficiency. The insulation has a major effect on the current distribution but little effect on the field produced by a given current at a distance.

On simple antennas, such as a straight wire, it is often possible to approximate the current as a sinusoidal distribution with an appropriate wave number. Such approximations have been developed for straight insulated wires by Guy and Hasserjian [4], King and Smith [5], and others. Once the current has been determined, the radiated field can be computed by using the field of a point source and integrating over the current.

A code has been developed combining the approximate current solution for a straight insulated wire with the field evaluation in a stratified medium. Thus, the field at a receiver location can be computed for a given input power to an insulated straight antenna as, for example, a wire in a tunnel in stratified earth. The calculated electric field above the ground due to a buried insulated dipole is shown in Fig. 2 as the length of the dipole is varied up to 20 miles and for receiver heights of 1 m and 10 km.

3. METHOD-OF-MOMENTS SOLUTION OF INTEGRAL EQUATIONS

For antennas that are more complex than a straight wire or when the current is needed to high accuracy, the approximate current solution is not usable. An accurate and versatile, although more computationally demanding, approach is the numerical solution of an integral equation for the current. A number of computer codes have been developed for this purpose using the method of moments to reduce the integral equation to a matrix equation for numerical solution. The kernel of the integral equation involves the field of a point source. Hence, the previously discussed solution for the field of a point source in the ground is needed.

3.1. WIRE OBJECTS

An integral equation code has been developed at LLNL for modeling wire antennas and scatterers. This code, the Numerical Electromagnetics Code (NEC) [6], solves the electric field integral equation for the current on wire structures. The thin wire approximation is used in which current in other than the axial direction on the wire and transverse variations in current are neglected. This code will accurately compute the current on wire structures with arbitrary shape and complexity.

NEC also includes a model for closed conducting surfaces based on the magnetic field integral equation (MFIE). Wires may connect to surfaces.

The integral equations are solved numerically by means of the method of moments. Spline current expansion and delta-function weighting is used for wires while surfaces are modeled with delta-function expansion and weighting. The resulting matrix equation is solved to yield an accurate numerical representation of the current which takes into account all interactions of the structure with itself and its environment.

NEC includes a number of features to provide a versatile model for antennas and scatterers. Excitation may be by an incident plane wave, multiple voltage sources, or the near field of a point source. Two-port networks and transmission lines may be modeled as part of the antenna. Wires can have finite conductivity or lumped loads consisting of series or parallel R-L-C elements.

The latest code, NEC-3 [7], can model wire structures above, below, or penetrating the surface of a homogeneous conducting ground. Interaction with the interface is included through the rigorous Sommerfeld-integral formulation. To achieve reasonable computation times on large structures, the Sommerfeld integral values are obtained by interpolation in precomputed tables, least-squares approximation, and asymptotic approximation.

NEC has been applied and validated for modeling a wide variety of antennas and scatterers. Examples of NEC calculations (Fig. 3) for a monopole antenna on a buried ground screen with variable number of radial wires [8] indicate the versatility of the code.

NEC is now being extended to model wires with dielectric or conducting sheaths including insulated wires in the ground. This will greatly extend the usefulness of the code for modeling buried antennas.

A code for modeling insulated wires by the integral equation method was developed by Richmond and Newman [9]. The effect of the insulation is included in the integral equation as the field of a radial polarization current in the insulation volume. This code does not include the effect of the air-ground interface. It can be used, however, to compute the current on deeply buried insulated wires of arbitrary shape. The method used by Richmond is being adapted to NEC, but will include the effect of the interface.

As we develop our in-house capabilities for modeling finite insulated antennas, we are evaluating the accuracy and limitations of Richmond's approach and the approximations used by King and others. In the future, it is also planned to extend the half-space model in NEC to stratified grounds.

3.2. ELECTROMAGNETIC SCATTERING FROM A SUBTERRANEAN 3-D DIELECTRIC

For more complex problems than can be handled by the techniques discussed above, Dease and Didwall [10] developed a modeling capability which evaluates scattering by an arbitrary three-dimensional dielectric body buried in a lossy half-space. The solution is formulated in terms of the dyadic Green's function of the magnetic vector potential type. This approach is a generalization to three dimensions of Richmond's [11,12] whole-space two-dimensional treatment of the scattering by a dielectric body. In addition, we include the effects of the interface.

In the future, we intend to extend this 3-D scattering code from the homogeneous half-space background to the stratified layered earth model.

4. TIME DOMAIN FINITE DIFFERENCE

This technique was first suggested by Yee [13] in 1966 as feasible with then available computers. It is based on an explicit time domain solution to the linearized version of the Maxwell equations in differential form. The technique was applied to a two dimensional body of revolution problem by Merewether [14] in 1971 and then extended to three dimensions by Holland [15] in 1977. All these problems considered perfect conductors. The codes were based on a separate field formulation that analytically described the incident field and computationally solved for the scattered field that first appeared at the scatter's surface to cancel the tangential component of the incident field. Only object exteriors were treated because computational resources were not great enough to model interiors of objects such as airplanes. Holland's code THREDE was validated by Kunz and Lee [16] against experiments (Fig. 4) in 1978.

A total field formulation by Taflove in 1980 [17] allowed lossy dielectric objects to be treated. At the same time, Kunz [18] generalized the separate field formulation so that lossy dielectric could be treated this way as well. This code was validated against Mie's classic analytic results for a dielectric sphere. An expansion technique was also developed by Kunz for increasing spatial resolution and allowing interiors to be modeled. Larger machines allow interior to be modeled directly, an avenue Taflove is aggressively pursuing as a consultant to LLNL. Kunz, using a VAX 11/780 and very long run times, has also modeled interior coupling directly [19] and validated the results (Fig. 5) against experiments made at the EMPEROR test facility (Fig. 6) at LLNL. Kunz and Breakall are now modeling simple antenna shapes, such as a radiating hole (Fig. 7) and will shortly be modeling more complex antenna shapes. The behavior of a buried antenna is also being investigated in a comparison time domain finite difference (TDFD) results vs. NEC results. Both perfectly conducting and lossy dielectric antennas are being considered for the TDFD technique, but only perfectly conducting antennas for NEC as a lossy dielectric antenna capability is under development but not yet available.

As can be seen from the array of capabilities, a rather complex lossy dielectric buried antenna problem can be treated with TDFD.

5. ABOUT THE AUTHORS

Jerry Burke is one of the main developers of electromagnetic antenna and propagation codes, the most notable one being "NEC." Jerry develops mathematical modeling methods and codes for applications in antenna design, geophysical exploration, communication applications, and electromagnetic propagation studies. Jerry's phone numbers are (415) 422-8414 or FTS 532-8414.

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Jim Breakall is conducting original research in EMP and microwave interaction with complex targets. Jim's research interests include antenna modeling using NEC and finite difference techniques. Jim's phone numbers are (415) 422-8196 or FTS 532-8196.

Edna Didwall is project manager and/or principal investigator for several research efforts involving remote detection, geophysics, and communications. Present research includes both theoretical and experimental methods. Edna's phone numbers are (415) 422-8800 or FTS 532-8800.

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R. J. Lytle is the group leader for the Electromagnetic and Acoustic Sensing Group. Jeff specializes in theoretical and experimental research in geophysical detection, subsurface imaging, and wave propagation theory. Jeff's phone numbers are (415) 422-9162 or FTS 532-9162.

R. J. King is a recognized authority in EM wave propagation theory. Ray has a particular interest in developing sensing methods in nondestructive evaluation. Ray's phone numbers are (415) 423-2369 or FTS 533-2369.

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FIGURE CAPTIONS

Figure 1. Calculations for a loop transmitter at a depth of 100 m in a homogeneous earth (half-space calculation) with conductivities 10^{-2}, $2x10^{-2}$, and $4x10^{-2}$ S/m. Both magnitude and phase are calculated. (Buettner, Burke, Didwall, Holladay, UCID to be released May, 1985)

Figure 2. Sample calculation for a buried electric dipole. Receiver locations at 1 m above the interface and at 10^4 m above interface are compared. (Buettner, Burke, Didwall, Holladay, UCID to be released in May, 1985)

Figure 3. Examples of calculations with NEC. (Burke, King, and Miller, UCID-20214, September, 1984)

Figure 4. F-111 Finite Difference Model (Kunz and Lee, IEEE Trans. Elect. Compat., Vol. EMC-20, No. 2, May, 1978)

Figure 5.1. Time Domain Comparisons at Test Point 3. Experiment (solid) and Compensated Computed (dashed).

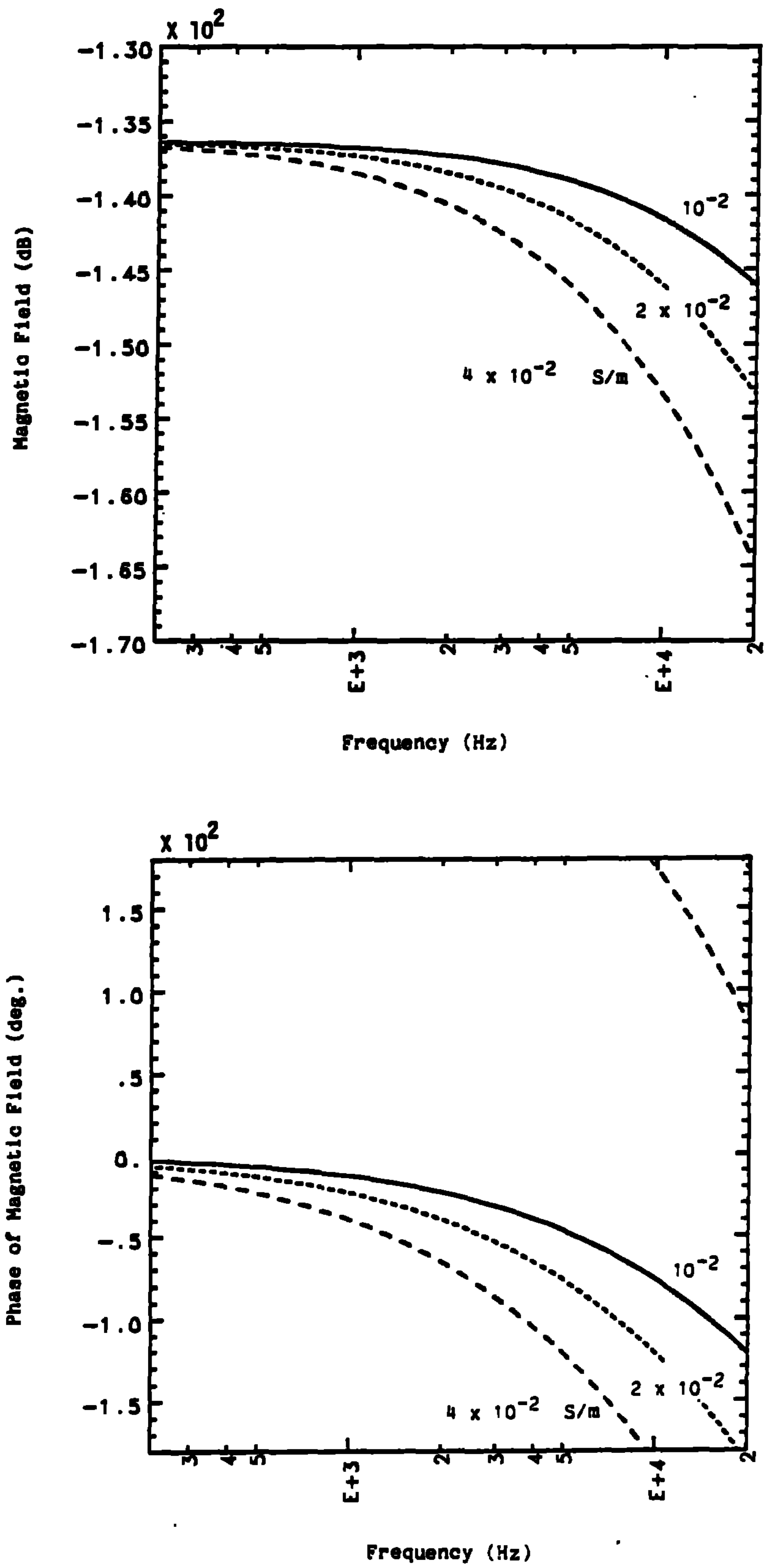
Figure 5.2. Fast Fourier Transform Comparison at Test Point 3. Experiment (solid) and Compensated Computed (dashed).

Figure 5.3. Power Spectral Density Comparison at Test Point 3. Experiment (solid) and Compensated Computed (dashed).

Figure 5. Interior Coupling Validation (Kunz, Hudson, and Breakall, submitted to IEEE Transaction on EMC, 1985)

Figure 6. Photo of the EMPEROR monocone showing the microwave absorber.

Figure 7. Modeling of Radiation Through an Aperture.



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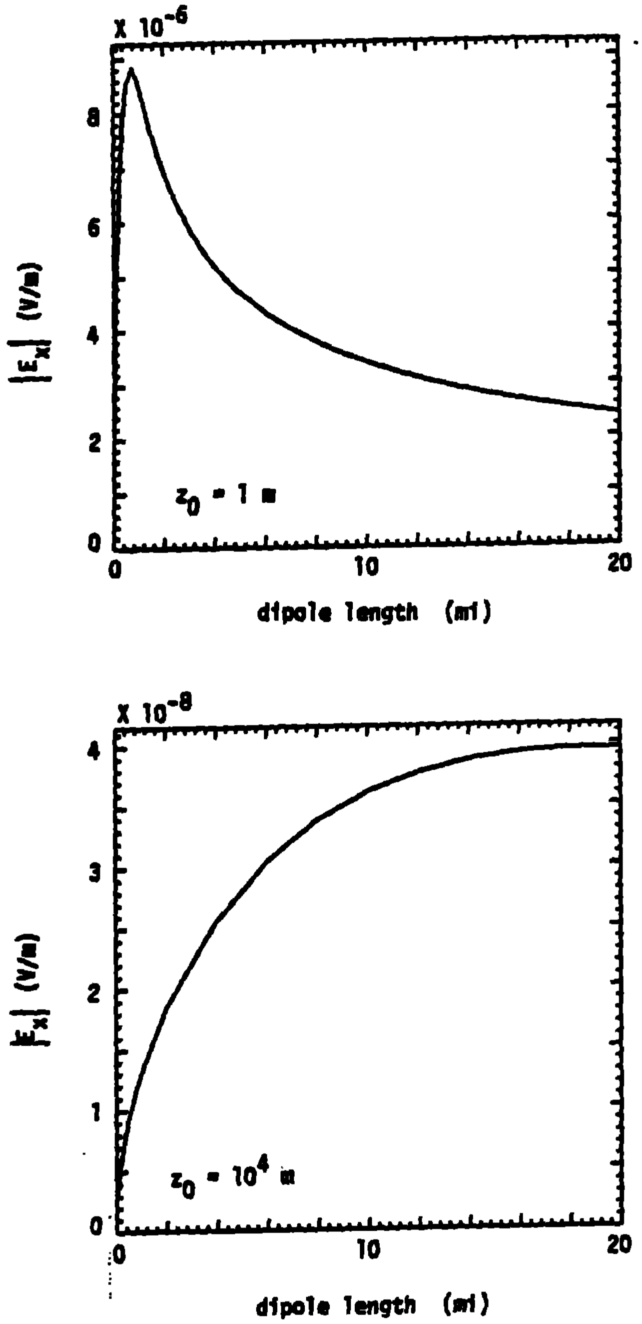


Insulated dipole:

Depth = 762 m

Input power = 1 watt

Frequency = 1 kHz

Wire radius = .0125"

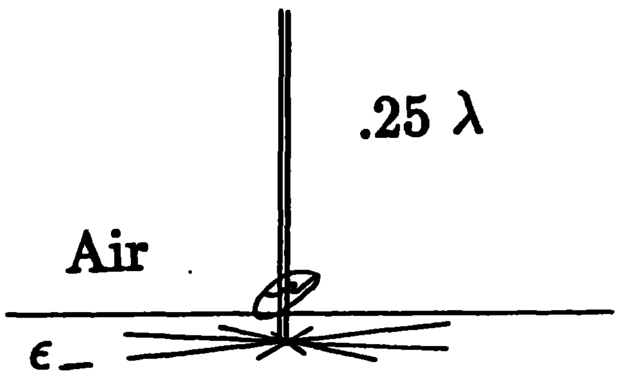
Insulation radius = 0.25" (air)

Lower halfspace:

Conductivity = 10^{-2} S/m

Figure 2. Sample calculation for a buried electric dipole. Receiver locations at 1 m above the interface and at 10^4 m above interface are compared. (Buettner, Burke, Didwall, Holladay, UCID to be released in May, 1985)

"RELATIVE COMMUNICATION EFFICIENTY (RCE)" COMPUTED WITH NEC-3 FOR A MONOPOLE ON A BURIED RADIAL-WIRE SCREEN PROVIDES A MEASURE OF ANTENNA PERFORMANCE TO COMPARE AGAINST COMPLEXITY OF THE GROUND SYSTEM AND THE COST OF POWER



N = NUMBER

OF RADIALS

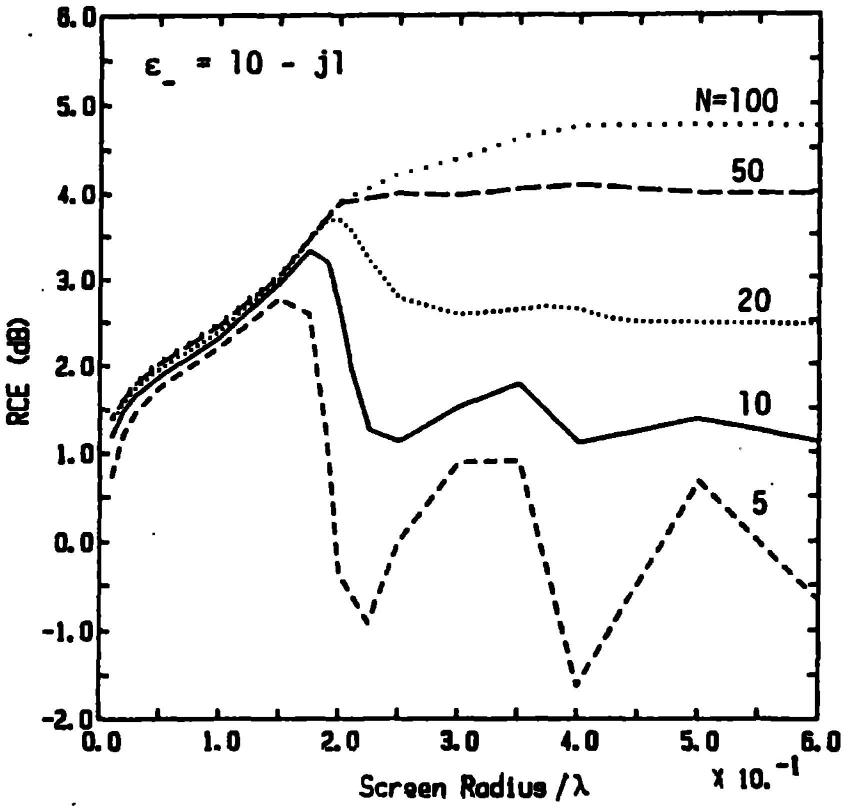
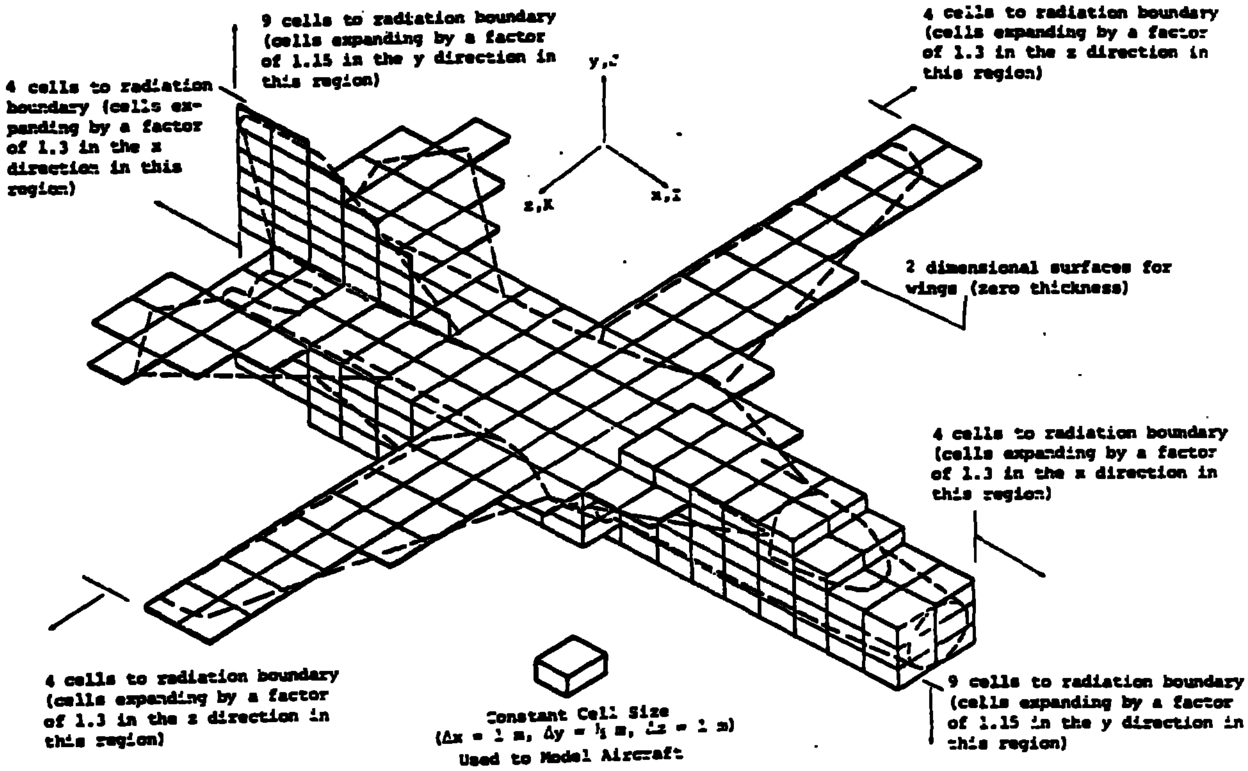
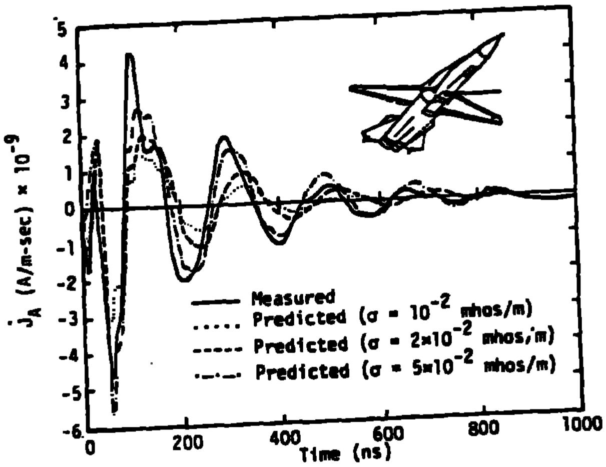


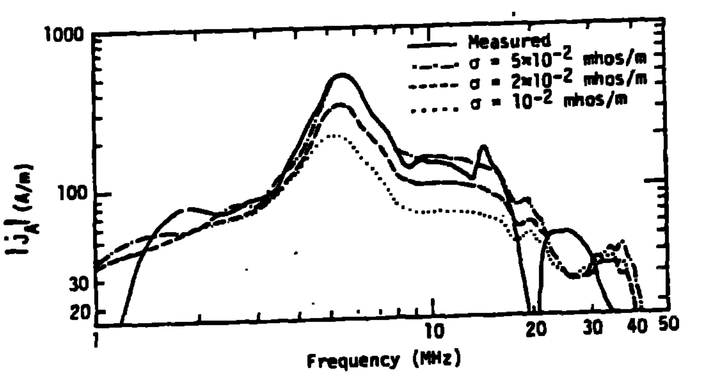
Figure 3. Examples of calculations with NEC. (Burke, King, and Miller, UCID-20214, September, 1984)



Model F-111 along with actual F-111 outline.

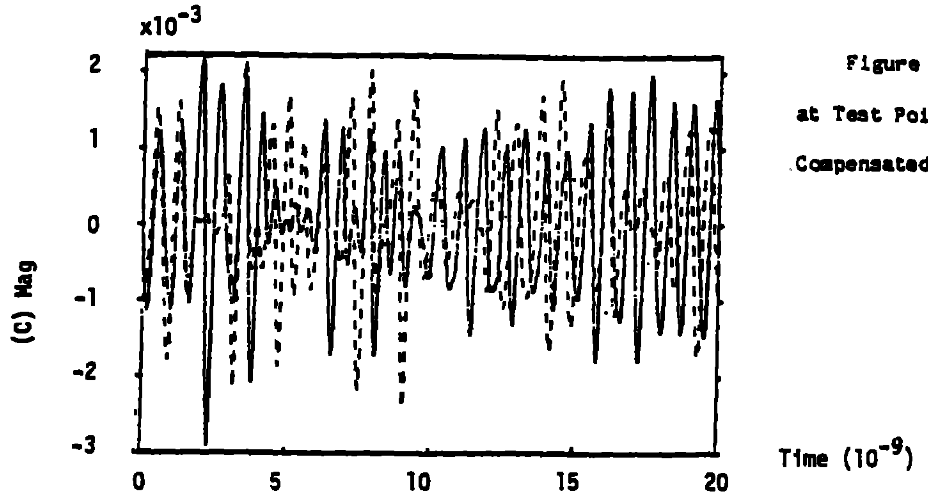


Time-domain response: Measured versus predicted response with three predictions using three different values of ground conductivity.



Study of ground-conductivity effects in the frequency domain.

Figure 4. F-111 Finite Difference Model (Kunz and Lee, IEEE Trans. Elect. Compat., Vol. EMC-20, No. 2, May, 1978)



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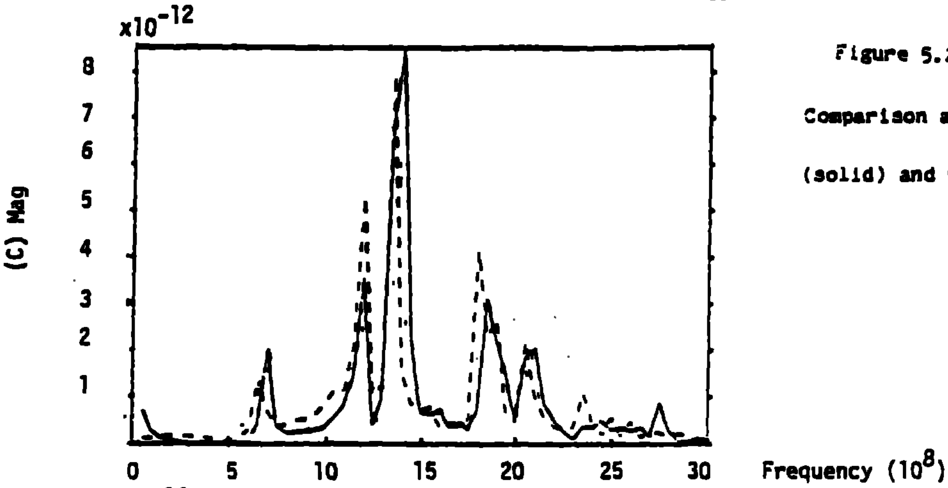

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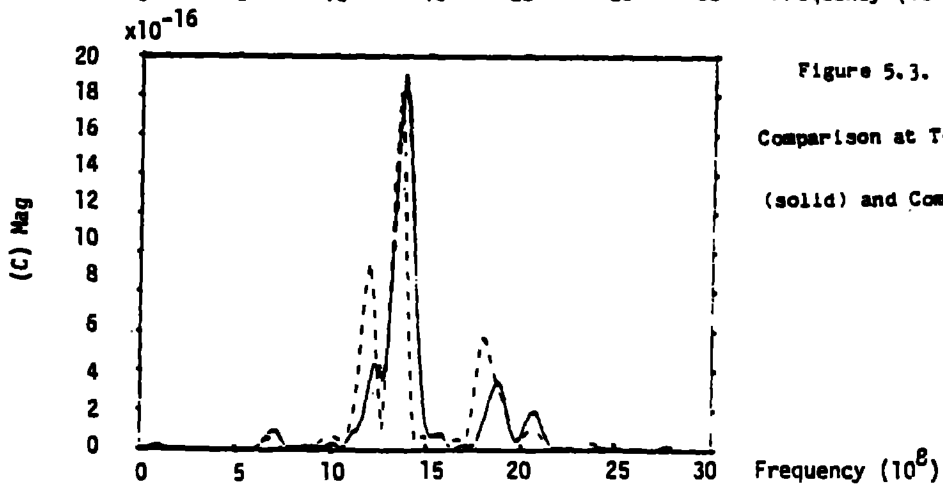

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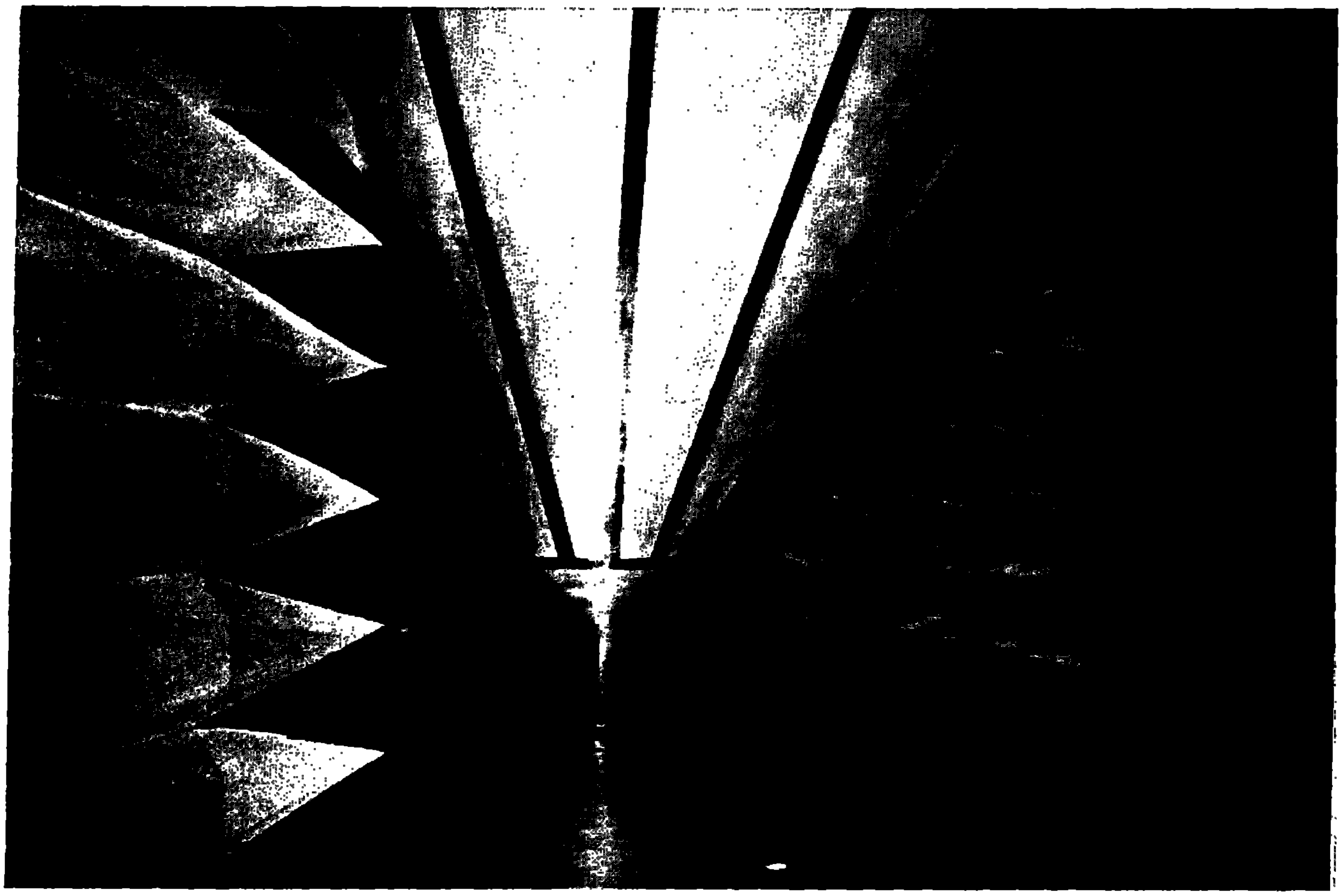

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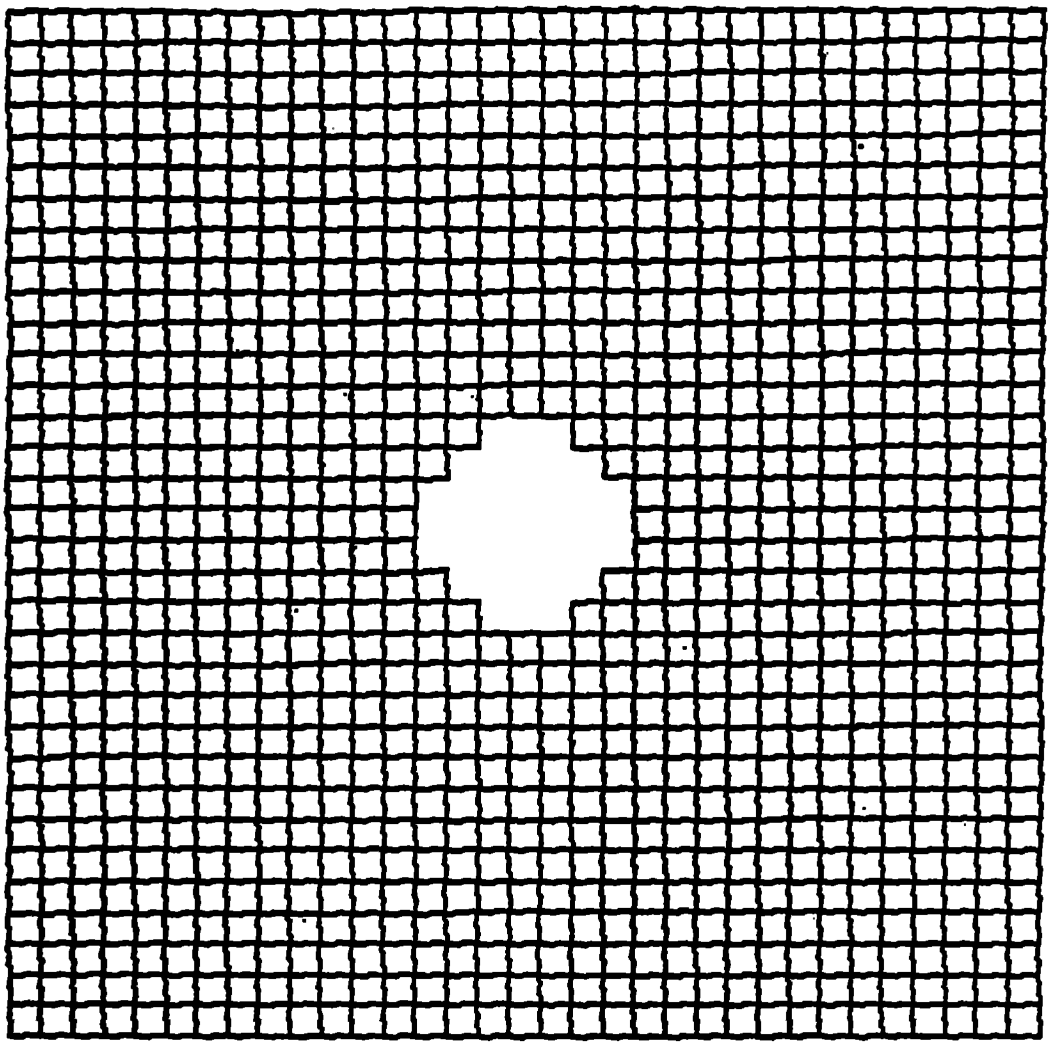

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